Measurements of a MIMO train-to-wayside communication system on tunnels

Juan Moreno , Leandro de Haro , Carlos Rodríguez , Luis Cuéllar and José Manuel Riera

***Abstract*— This paper presents a deep insight on a real implementation of a train-to-wayside radio on subway tunnels that makes use of a 2x2 MIMO-OFDM setup. The following parameters on the performance of such a system are investigated: polarization diversity, antenna separation, tunnel cross-section influence and MIMO capacity. Moreover, two different channel matrices have been calculated, assuming uniform power allocation and performing the waterfilling algorithm. Finally, the purpose of this paper is to evaluate the feasibility of a real MIMO-based train-to-wayside broadband radio. Measurements were carried out on Line 3 of Metro de Madrid, Spain.**

I. INTRODUCTION

As modern train systems like high-speed railways or subways get more complex, the requirements for train-to-wayside radios become more demanding [1]. The need of safety, short intervals between trains and real-time video-based services imply large bandwidths, short delays and efficient QoS mechanisms. In a hostile environment like underground tunnels, having a helpful technology to provide all these services is a great step forward. The purpose of this paper is to check if MIMO is a suitable technology in the points commented before.

In this paper we provide measurements of the performance of a 2x2 OFDM-MIMO system in the most realistic and exhaustive way possible (this is, real trains in operation). The influence of the following parameters is investigated: polarization diversity, antenna separation and tunnel cross-section.

II. MIMO AND PROPAGATION IN TUNNEL

A. Propagation in tunnel

There are two different scenarios related to radio propagation inside a tunnel: natural propagation within the tunnel and leaky wave propagation. The first one is the scenario of application in this paper. The second one is very common on subway tunnels and needs a leaky coaxial in the trackside. Propagation is very different on each one of them.

B. MIMO

MIMO is likely to be a suitable technology to be used in tunnels. The improvement of the capacity due to this technology is helpful under both heavy multipath conditions and low signal to noise ratio both of them very likely to happen in tunnels [2]. The aim of this paper is to prove both statements with measurements carried out in real in-operation conditions for a train-to-wayside system.

III. GENERAL ARCHITECTURE OF THE MIMO TESTBED

In order to carry out these measurements we opted for a Testbed already developed by some members of this group [3]. This testbed makes use of an implementation of both DVB-T2 transmitter and receiver. The reason of this choice was our need of OFDM, diversity and the fact that we could work at 594 MHz (both an unused channel and also in a band valid for railway purposes). LTE's broadcast mode was not developed already, so we opted for DVB-T2. We only made use of the transmission part and the frame structure of DVB-T2 (including pilot patterns for channel estimation), because this standard does not implement MIMO, it uses MISO instead. We chose MIMO-OFDM because this is the technology used in LTE for the downlink and LTE has been identified as the future standard for railway communications [4].

TABLE I
MAIN PARAMETERS OF THE MIMO TESTBED

Parameter	Symbol	Value
FFT mode	-	2K
Guard Interval	GI	1/8
Scattered pilot pattern		PP1
Modulation	-	64QAM
Sampling frequency	F_s	9.1429 MHz
Useful symbol time	T_u	$2048/F_s$=224 µs
Guard time	T_g	$T_s/8$=28 µs
Symbol time	T_s	252 µs
Bandwidth	BW	8 MHz
Data subcarriers	N_d	1878

The testbed has three main modules: DSP, RF and antenna array. We have two antennas on both transmitter and receiver side (2x2 MIMO). Data signals are generated offline (in a PC) before starting measuring. These signals are delivered to the DSP platform and transmitted at intermediate frequency to the RF module. In this module, signals are upconverted to the RF frequency, amplified, filtered and transmitted through the antenna array.

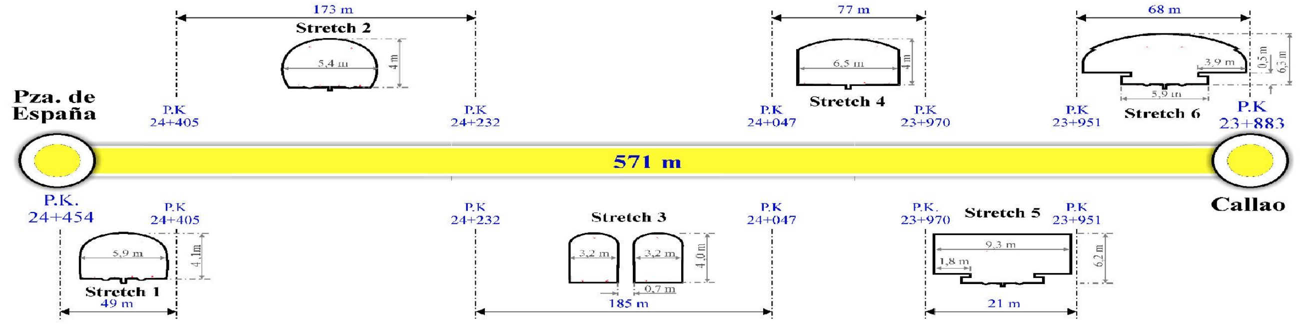

Fig. 1(a): old tunnel cross-sections (Callao – Plaza de España).

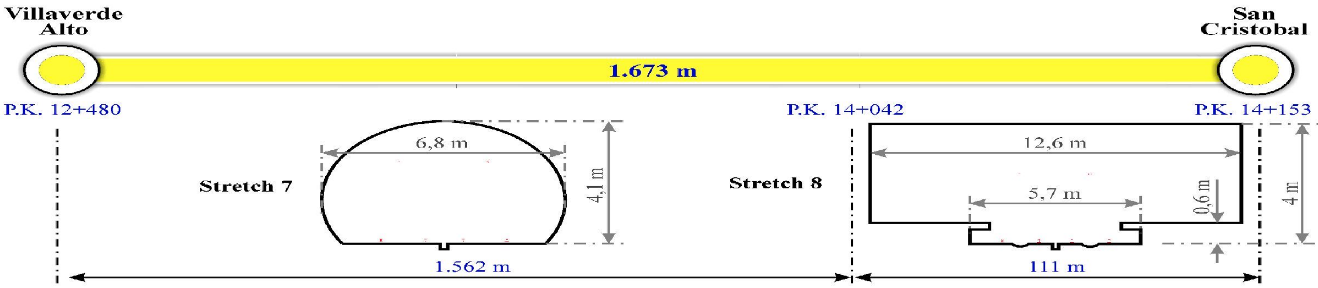

Fig. 1(b): new tunnel cross-sections (Villaverde Alto – San Cristóbal)

In the receiver side, signals are downconverted, amplified and filtered in the RF module. DSP performs synchronization and FFT demodulation tasks before delivering the information to the PC. This testbed estimates MIMO channels based upon DVB-T2 pilot subcarrier pattern.

Figure 2: antenna element.

On the transmitter side, an RF module receives signals at 36 MHz (IF frequency) and upconverts them to 594 MHz (RF frequency). It also amplifies and filters the signal. On the receiver side, a low noise amplifier (LNA) with a noise figure of 1.1 dB is used. Both signals are also filtered and downconverted (from 594 MHz to 36 MHz). A variable attenuator is used to adjust received signal power levels. The input power was 2 W at each one of both antennas on the transmitter. In order to make design and installation on the rolling stock simple, in this research work we chose a short dipole (see Fig. 2 for a picture of the dipole).Dipole antennas get more profit from multipath instead of a directive Yagi-Uda antenna. The main parameters of the testbed are listed in Table I.

IV. EXPERIMENTAL ACHIEVEMENTS

A. MEASUREMENTS

Using the MIMO testbed described in Section III we carried out a measurement campaign on Line 3 of Metro de Madrid. We made measurements on copolarization and cross polarization. All of them were performed on two very different tunnels (one with a smooth cross-section and the other with frequent changes in the section, see Fig. 1a and 1b), and two antenna spacing within arrays (λ and λ/2). So we have measured in 16 different scenarios (2 tunnels x 4 polarization setups x 2 antenna spacing). As it was stated before, for each one of these 16 scenarios, we computed 2 MIMO capacities (waterfilling and equal power allocation). Each measurement was carried out twice to provide more reliable results. In Fig. 1(a) and 1(b) cross-sections for both tunnels are shown.

We performed our measurements on two different stretches of Line 3 of Madrid Subway. The first one was between Plaza de España and Callao and the second one was Villaverde Alto – San Cristóbal. The interstation Callao-Plaza de España was built in the late 30's of the 20th Century and the construction method of the tunnel was the so-called 'cut and cover', that consists on excavating a trench and then roofing it over with an overhead support. It is a shallow tunnel that goes below Gran Vía and its cross-section varies significantly in a short distance, due to columns and other obstacles (see figure 1a). Its length is 571 m. The interstation Villaverde Alto-San Cristóbal 1.718 meters long) opened in

2007 and it was entirely carried through using a boring machine, so the cross-section of the tunnel is very uniform (see figure 1b).

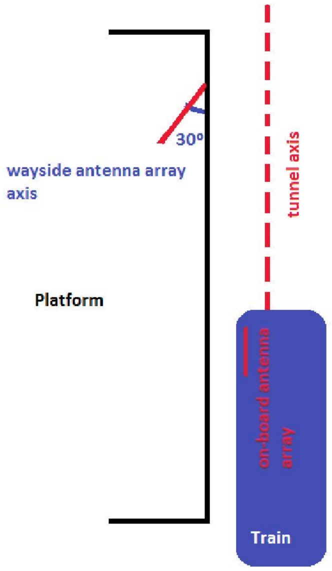

Fig. 2: Sketch of the measurements in line 3 of Metro de Madrid.

All these measurements were performed with trains at real in-operation conditions with on-board antennas placed on one side of the train and wayside antennas, at the end of the platform (see Fig. 3), to make sure that the results were applicable in real world.

B. RESULTS

Here we show the results retrieved from this measurement campaign. We provide data about the influence on MIMO capacity of polarization, antenna spacing within the array and a discussion on the advantages of a waterfilling power allocation scheme instead of a uniform one.

Some of these results were expected (MIMO overcomes SISO) and others not so much. A good example of this can be seen in Fig. 3, where we show the CDF of the capacity for waterfilling on one of the tunnels, with an antenna spacing in the array of λ. The vertical-vertical polarization is clearly overcome by the horizontal-horizontal one, and also by the horizontal-vertical one.

In Fig. 4, we also provide a comparison (in terms of capacity) of the performance of the system in the two tunnels depicted in Fig. 1a and 1b. This comparison makes sense because very often tunnels' cross-sections are very different from each other even within a single subway line. We measured on a tunnel excavated with a boring-machine, so we have almost no changes in the cross-section.

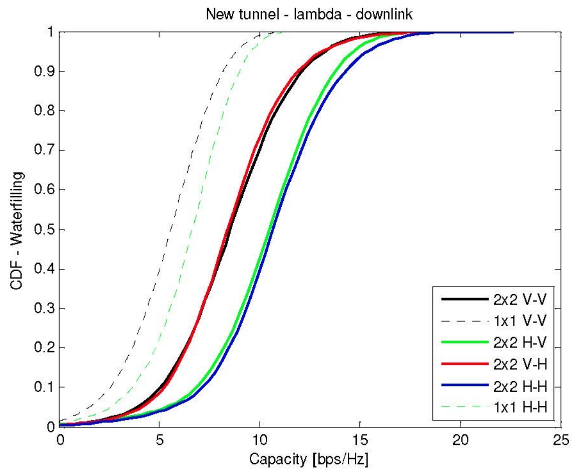

Fig. 3: Influence of polarization on CDF Capacity (bps/Hz) (equal power allocation).

On the other hand, the old tunnel was manually excavated, so there are many changes in the cross-section. This is an important matter that is usually forgotten when a radio system is deployed in a tunnel. From the results of Fig. 4 we can see that old tunnel is better in terms of capacity. We attribute this fact to the frequent changes in the cross-section of the tunnel, because each one of these changes excites (ideally) infinite new propagating modes.

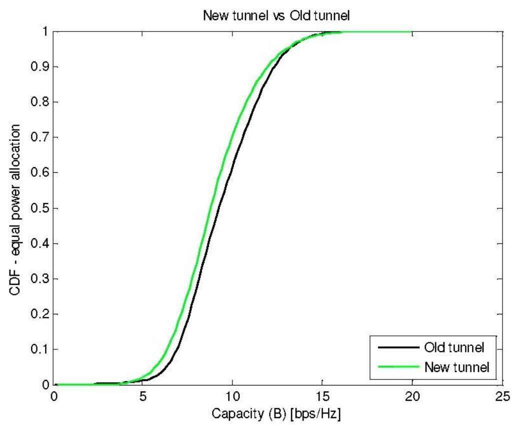

Fig. 4: Influence of tunnel's cross-section on capacity (bps/Hz) (equal power allocation)

Another result provided was the significant increase of capacity if we double the antenna spacing within both arrays. In Fig. 5 we see that λ-spaced arrays overcome λ/2–spaced arrays clearly in terms of capacity. This is due to the lower correlation between antenna elements within the array. This result is more predictable a priori than the others.

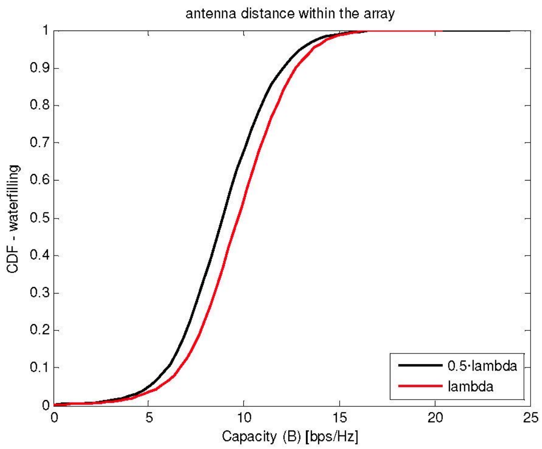

Fig. 5: influence of antenna separation within the array on capacity (bps/Hz) using waterfilling algorithm.

Finally, we compare waterfilling algorithm and equal-capacity allocation in the same terms as before. The result is that only in few occasions using waterfilling algorithm leads into an increase of capacity. In Fig. 6 we depict a very concrete scenario (vertical polarization, $\lambda/2$ spacing) but in almost every scenario, both strategies of power allocation provide the same result. So we conclude that, being the waterfilling algorithm a more complicated one, it is not worth to use it on train-to-wayside communications in tunnels.

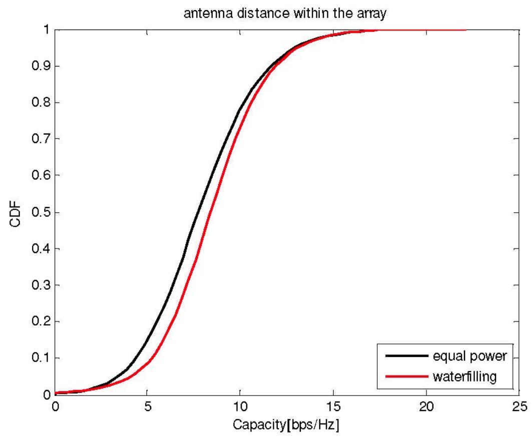

Fig. 6: influence of power allocation schemes: waterfilling algorithm and equal power allocation

V. CONCLUSION

Railways are changing rapidly and it is mostly due to improvement on information technology systems. Here we focused on the train-to-wayside radio, especially on checking the feasibility of a MIMO system in tunnels, in a real in-operation scenario (see Fig. 7). A large set of measurement were carried out, and provided some relevant results.

The most important results are that the waterfilling algorithm does not imply a significant increase in the performance of the system, and because of its higher complexity (compared with its uniform alternative) it is not worth it. Another relevant result is derived from the influence of polarization, where the horizontal one has the best results in terms of capacity. This is a useful result for real deployments.

Fig. 7: wayside devices on the left side of the picture and the on-board antenna on the cabin door of the train

The last relevant result is the importance of the changes in the cross-section of the tunnel in capacity. Sometimes, tunnels with frequent changes on its cross-section also imply difficulties in the propagation. Our measurements demonstrate that MIMO could be the solution for some of this kind of problems. Of course, this problem should be addressed in a more exhaustive way (for example, at a wider range of frequencies or in different tunnels), but it is a good starting point. Finally, another two minor results coherent with the literature [5]: in tunnels, MIMO overcomes SISO; and more separated antennas provide better results in terms of capacity.

REFERENCES

[1] S. Morar, "Evolution of Communication Based Train Control Worldwide", IET Professional Development Course on Railway Signalling and Control Systems (RSCS 2012), 2012, p. 218 - 226.

[2] M. Lienard, P. Degauque, J. Baudet and D. Degardin, “Investigation on MIMO Channels in Subway Tunnels”, IEEE Journal on Selected Areas in Communications, 2003, Vol.21, Issue 3, pp. 332 – 339.

[3] C. Gómez-Calero, L. Cuéllar, L. de Haro and R. Martínez, “A 2x2 MIMO DVB-T2 system: design, new channel estimation scheme and Measurements with polarization diversity”, IEEE Transac. On Broadcasting, Vol. 56, Num. 2, Jun. 2010, pp. 184-192.

[4] LTE/SAE -The Future Railway Mobile Radio System? Long-Term Visions on Railway Mobile Radio Technologies, UIC, V 0.4 Draft 14.09.2009.

[5] B. Izquierdo, S. Capdevila, L. Jofre, and J. Romeu, "Evaluation of MIMO Capacity in Train Tunnels", 2007 IEEE Antennas and Propagation Society International Symposium, 9-15 June 2007, pp. 1365 - 1368.